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Simulation of an Exhaust Heat Driven Rankine-Cycle for Heavy-Duty Diesel Engines

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Abstract

High-efficiency vehicle engines play an important role in the context of low-carbon cities. An auspicious approach to reduce the emissions of internal combustion engines and make them more fuel efficient is exhaust heat recovery by an Organic Rankine Cycle (ORC). The present study focuses on the simulation of ORCs for exhaust heat recovery in heavy-duty diesel engines for mobile applications, e.g. trucks, rail vehicles and ships. An exceptional challenge associated with these applications are variable engine load profiles, causing the partial load operation of the ORC to gain significant importance. Furthermore, the different system components are highly depending on another. Hence optimizing a single part of the ORC does not necessarily lead to an improvement of the overall system. The level of detail of the simulation models has a considerable influence on their ability to reflect and predict the real operating performance of the system. While rather simple potential analyses promise the capability to recover large amounts of heat, detailed simulation models of a first prototype predict significantly lower recovery rates. Still, the simulation results confirm the process feasibility with fuel savings and therefore emissions reductions of up to 3%.

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Keywords: Organic Rankine Cycle; Exhaust Heat Recovery; Diesel Engine; Waste Heat; Simulation

1. Main text

In times of depleted petroleum supplies, greenhouse effect and stringent environmental emission regulations, it is an important challenge to improve the efficiency of internal combustion engines. About one third of the fuel-bound energy gets lost through waste heat in the exhaust gas, which makes the recovery

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of exhaust heat an auspicious approach to improve the efficiency of internal combustion engines and to lower their emissions. This study focuses on the simulation of ORCs for exhaust heat recovery in heavy duty diesel engines in trucks, rail vehicles and ships. Simulation results provide a basis for potential analyses and the dimensioning of system components.

Nomenclature

Abbreviations

ORC	Organic Rankine Cycle
Symbols	
c	rotational speed [m/s]
$\dot{H}$	enthalpy rate difference [kJ/kg]
p	pressure [Pa]
s	entropy [kJ/(kg K)]
T	temperature [K]
η	efficiency [-]
Subscripts	
in	inlet
is	isentropic
out	outlet

2. System description

In an earlier investigation a comparative assessment of different cycle processes for exhaust heat recovery was carried out. As a result, the ORC was found to be the most promising option. Furthermore, ethanol as working fluid turned out to have the most advantageous properties for this specific case of application. [1]

2.1. System Constraints

Regardless of the system design, the power output of the ORC and thus the achievable fuel savings are limited by some substantial restrictions like the available exhaust heat and recooling power, the temperature of the heat sink, the packaging and limited space for the system components or a minimum tolerable exhaust gas outlet temperature to avoid acid condensation.

A further challenge associated with heavy-duty diesel engines in mobile applications are highly variable engine load profiles, resulting in fluctuating exhaust temperatures and mass flow rates and thus in an unsteady heat source for the ORC. For this reason, the ORC should not be designed for one specific engine operating point, but for the entire engine load profile. This represents a major difficulty for simulating and dimensioning the process.

2.2. System Design

The most crucial components are the expansion device and the exhaust gas heat exchanger linked to the question of how to run the process. In the heat exchanger the working fluid can be superheated or partially heated. Depending on the selected working fluid a superheated cycle can be advantageous or disadvantageous and the expansion process can be wet or dry. While for some expansion devices wet expansion can be beneficial, others require dry expansion.

Preliminary design studies with ethanol as working fluid showed, that the saturated vapor cycle is the most appropriate process. While superheating causes poorer utilization of the available exhaust heat, partial heating may lead to problems concerning the expansion device due to enlarged moisture levels and condensate quantities during the expansion process. As seen in Fig. 1, even in a saturated vapor cycle it has to be expected that the working fluid will partially condensate during the expansion process, since ethanol is a wet organic fluid with a negative slope of the saturated vapor line. Therefore it is necessary to select an expansion device, which cannot be damaged by liquid droplets.

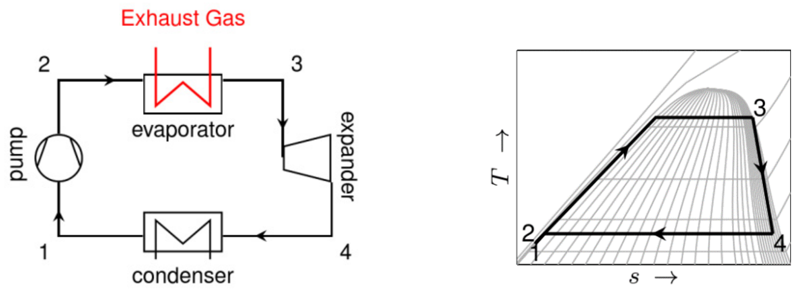

Fig. 1 saturated vapor ORC for exhaust heat recovery with ethanol as working fluid: (a) schematic diagram (b) temperature-entropy diagram

2.3. Expansion device

The Chair of Fluidics of the TU Dortmund University carried out an application-oriented design approach in order to design and dimension a suitable expansion device. Due to the fact that the system components are highly depending on another and thus optimizing a single part of the ORC system does not necessarily lead to an improvement of the overall system, the expansion device was designed focusing on the overall process and not just on the machine itself. A screw-type steam expander was chosen, because these expanders allow for efficient energy conversion in the lower and medium power range with a wide scope of operation. Both geometric parameters of the expansion device and system parameters of the ORC were varied to find the appropriate expander geometry for maximum achievable overall power output over the entire engine load profile. [2]

2.4. Heat Exchanger

The evaporator and the condenser are of the plate heat exchanger type. Compared to other heat exchanger types, plate heat exchangers are particularly compact, are less vulnerable to fouling and are highly suitable for this specific purpose. The plate heat exchangers for the different system applications regarded in this study were designed by external suppliers. The precise internal geometry is not known, but their performance was measured on test benches.

3. Simulation

First potential analyses promise a high capability to recover large amounts of heat. The achievable fuel savings can be comparatively high in some engine operating points. Even under consideration of the aforementioned restrictions averaged fuel savings over the entire load profile can be estimated with over 5% for most system applications.

By successively increasing the level of detail of the simulation models and adopting the actual physical and geometrical properties of the system components of a first prototype it can be shown, that partial load performance has a crucial impact on the overall power output and that the initially estimated efficiency cannot be reached.

3.1. Expansion device

To simulate the performance of the expander, many studies assume constant isentropic efficiencies with typical values of around 70-80%.

To predict the operating behavior of the screw-type steam expander considered in this investigation, a multi chamber model simulation was carried out [2]. The isentropic efficiency depends on different system parameters like inlet temperature, inlet and outlet pressure and circumferential speed of the rotors.

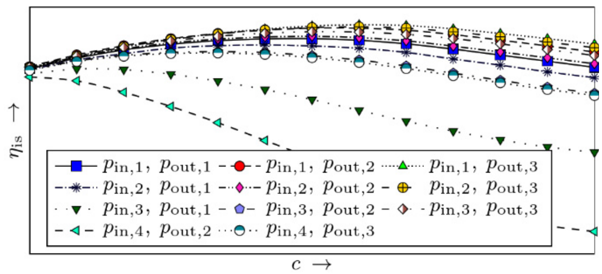

Fig. 2 Varying isentropic efficiencies of a screw-type expander in dependence of inlet and outlet pressure and circumferential speed for a saturated vapor ORC

Due to the aforementioned predominant partial load performance, the assumption of constant isentropic efficiencies is not justifiable. In the case considered here, the isentropic efficiency will generally differ from its nominal value, as seen in Fig. 2. In [2] it was also shown, that the expander with the most promising overall performance only reaches moderate isentropic efficiencies well below the usually assumed values.

3.2. Heat Exchanger

To predict the performance of the heat exchanger, the first step is usually a calculation using simple energy balances and assuming minimum pinch point temperature differences or constant heat transfer coefficients, while neglecting the actual physical properties of the heat exchanger.

Fig. 3 shows exemplarily one possible flow arrangement of a plate heat exchanger for exhaust heat recovery. Plate heat exchangers can be designed with multiple passes for each fluid. Complex flow arrangements are used when there is a significant difference in the flow rates of the two fluid streams and in the allowable pressure drops [3]. Typically this is the case with exhaust gas on one side and a working fluid on the other side. In general, it is recommendable that the working fluid with considerably lower mass flow rates goes through multiple passes.

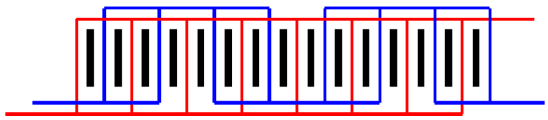

Fig. 3 1 pass - 4 pass plate heat exchanger

Fig. 4 qualitatively shows temperature - enthalpy rate difference diagrams for both an assumption of a minimum pinch point temperature difference as well as for a realistic examination of a 1 pass – 4 pass flow arrangement in overall counter flow.

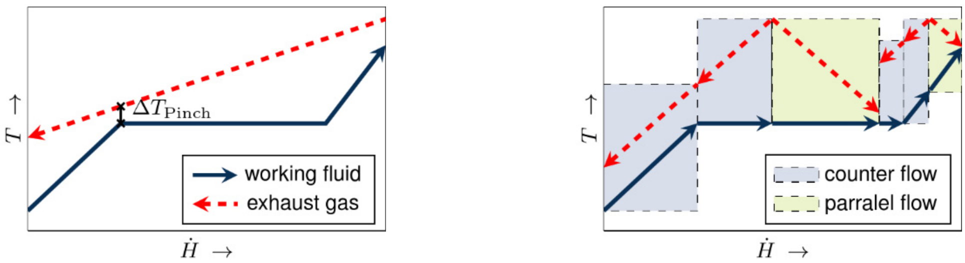

Fig. 4 temperature - enthalpy rate difference diagram: (a) 1 pass – a pass (b) 1 pass – 4 pass

In the realistic model it can be seen, that the heat exchanger is a complex interconnection of different counter- and parallel flow modules and the pinch point assumed in the simple model actually does not exist.

4. Results

Fig. 5 shows simulation results for first prototypes for the marine- and the rail-application. The achievable fuel savings in most operating points lie significantly below the initially estimated 5%. Averaged fuel savings are highest for the marine application and reach a value slightly above 3%. Due to the fact, that the exhaust gas temperatures and mass flow rates are comparatively high and there are no significant recooling capacity restrictions, the marine application is superior to the other applications. Based on these results, the prototypes can be further optimized to maximize the overall power output of the ORC.

5. Conclusion

On one hand the present study shows, how important it is to accurately model the system components in simulation tools with a high level of detail, due to the fact that the system operates in partial load most of time. Simple models can provide a valuable approach to predict the systems performance, but when it comes down to dimension the system components and to precisely calculate their partial load performance, geometrical properties should be taken into account.

On the other hand it confirms, that the ORC for exhaust heat recovery is an auspicious approach to lower emissions of vehicle engines and considerable fuel savings can be proved. It can contribute to urban transportation with efficient energy and low emissions in low-carbon cities.

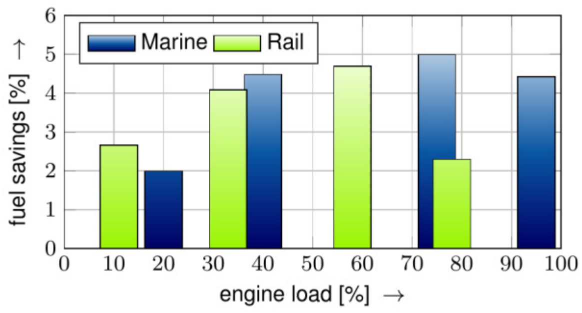

Fig. 5 Simulation results - Fuel savings in dependence of engine load for different system applications

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Biography

Jan Wiedemann is research associate at the Thermodynamics institute of Ruhr-University Bochum. Roland Span is chair of this institute. Research areas of the institute include the simulation of innovative energy processes, the accurate experimental and theoretical representation of thermophysical properties, selected heat transfer and sorption problems and technical biogas processes.